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FIELD OBSERVATIONS IN NORTHERN NORWAY BEARING ON MAGMATIC DIFFERENTIATION

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Recent years have witnessed a marked development in the understanding of differentiation processes. Petrographers have tried to get away from the purely theoretical considerations about the matter and to harmonize the conclusions from the field observations with the results of synthetical experiments on silicate minerals and their crystallization obtained by the Geophysical Institute at Washington and others. Although these experiments are still far from covering all subjects involved, and although the multitude of field observations from most parts of the earth are often contradictory, there seem to be certain lines of development which prove promising.

The results now generally converge toward the conclusion that an ordinary fluid silicate magma, without concentrated mineralizers, is not capable of splitting up into two magmas mutually insoluble or with limited solubility. Accordingly, the main part of the differentiation processes is transferred to the period of crystallization, resulting in considerable restriction of possibilities.

According to this supposition, naturally the first mode of separation to be considered was that of the heavier crystals from the lighter ones and from the still fluid magma by gravitative settlement. In a number of instances this sort of differentiation has definitely been proved to occur. But it also became obvious that this sort of separation could not alone account for a great many differentiation processes actually observed.

The newer theory of squeezing differentiation—quite as well in accord with the latest results—seems to be capable of a more general application in those very frequent instances where lateral

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pressure prevailed during crystallization. This theory was suggested by A. Harker, and especially after it had been formulated and developed by N. L. Bowen¹ it has aroused keen interest among petrographers. In the present paper I have attempted to give some examples from northern Norway bearing on this sort of differentiation.

SHORT REVIEW OF THE GENERAL GEOLOGY OF CALEDONIAN

As known, the Caledonian mountain chain—of late Silurian to early Devonian age—traverses the whole length of Norway from SSW. to NNE., in its northern part occupying nearly the whole breadth of the country. The axis of the chain forms a marked geosynclinal depression of the old Archaean Scandinavian shield and of the pre-Cambrian peneplain. The depression is filled with a very thick series of sediments, strongly folded and metamorphosed.

It is supposed that the whole of Scandinavia has been covered by the Cambro-Silurian sediments, remnants of which are found at many places above the Archaean rocks. They are unmetamorphosed and unfolded wherever well beyond the Caledonian folding region. Toward this old mountain chain, first folding sets in, then we meet an increasing degree of metamorphism, which attains its maximum at the axis of the chain. In the same direction the thickness of this series of sediments increases markedly. In the eastern, unfolded zone (especially in Sweden) the total thickness is generally only some few hundred meters, in the folded but unmetamorphosed Kristiania region the thickness surpasses 1,000 m., and toward the mountain chain it reaches several thousand meters.

Although no determined fossils have yet been found in the metamorphosed sediments of *northern Norway*, there are several reasons to believe that the sediments here represent the same Cambro-Silurian series. The original sediments in the geosyncline were extensive layers of slates, marls, limestones, and dolomites, with subordinate sandstones. The metamorphism has been

¹ N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, Vol. XXIII (1915), suppl.; "Crystallization-Differentiation in Igneous Magmas," *ibid.*, Vol. XXVII (1919), pp. 393 ff.

very strong throughout the region, producing garnet-mica schists, marbles, quartzites, etc., but generally not with the development of lime-silicate minerals.

In this region there has not been disclosed any unconformity or discontinuity in the sedimentation.

During the Caledonian folding this series was intruded by great masses of eruptive rocks, especially in the axial part of the chain. Most of these are ordinary granites.

There also occur in considerable quantities femic eruptives, very intimately intruded in the schists, and like these thoroughly metamorphosed to amphibolites and different eruptive gneisses. They are much differentiated, the last products generally being soda-rich granites (or Trondhjemites).

Moreover, we find as isolated fields more extensive areas of gabbroidic eruptives, less metamorphosed, sometimes nearly fresh. They were also intruded during the Caledonian folding period and are chemically nearly associated with the former group, from which they do not differ very much, if at all, in age. They also show marked differentiation and on account of their relative freshness afford very interesting petrographical material.

All the eruptives seem to belong to the same cycle of orogenic intrusions. Original lavas or tuffs, which occur in great masses in the Trondhjem district farther south, have not yet been identified among them.

The intrusions have everywhere occurred under a heavy load of sediments, and the whole complex must have been heated to a considerable temperature.

Outside the real root of the mountain chain all eruptives seem to have been intruded completely parallel to the schists. Especially in the district to be considered here, we nowhere find crossing eruptive dikes or other eruptive bodies cutting the schistosity (excepting the pegmatite dikes). It seems to have been a general rule that the magmas, after intrusion, were subject to *magmatic migration* between heated schists, from the root of the mountain chain outward. In this way the magmas may have wandered for very considerable distances from the places where they broke into the schists, until they came to rest. The moving force was induced

by the orogenic folding itself, and lateral pressure existed throughout the crystallization period.

THE RAANA NORITE FIELD (FIGS. 1 AND 2)

This eruptive body, to be especially considered here, is situated at the south side of the Ofoten Fjord, west of the known harbor of Narvik, at $68^{\circ}20'$ latitude. It has recently been closely investigated by the author on account of discoveries in the last years of extensive but poor deposits of nickeliferous pyrrhotite.

In the very rugged country with steep mountains rising directly from the sea and differences in height of more than 4,000 feet, the whole eruptive mass is exceedingly well exposed, and the results of differentiation can be followed in all details.

The norite is injected into a thick series of garnet-mica schists with some interstratified layers of marble. The injection is parallel to the schistosity and forms a lens-shaped body with a thickness of about 3,500 m. and a diameter of about 12 km. The relative thickness of the lens is greater than is generally the case in this sort of intrusions, and is supposed to be due to the influence of some E.-W. folding axes. The section of the eruptive body with the present surface has an area of 67 km.², 3 km.² of which has been cut off by erosion. No offsets or crossing dikes occur in the surrounding schists.

The very first investigation teaches that the norite field is not homogeneous throughout, but is composed of a central mass of *quartz-norite* and a very considerable and continuous marginal zone of more femic *normal norite*, occupying the border against the schist all around the field to a width of one-third to one-fourth of the whole diameter.

To understand the reason for this, it is important to know the tectonic position of the eruptive mass. One might of course be tempted to believe that the field after differentiation might have been thrown down in an inverted fold, and that the basic border zone accordingly should represent the lower part of the magma basin, separated out by gravitative differentiation in the same way as is the case in the Sudbury field. This, however, is definitely

proved not to be the case. The norite body forms a lens in its normal position between the schists, with a mean dip of about 30° , and the basic border zone is quite as well developed in the upper as in the lower part of the lens.

Between the quartz-norite and the normal norite there is no eruptive contact, but a gradual though rapid transition.

As a third group we may unite all the olivine-bearing rocks: *lherzolites*, *troctolites*, and *olivine-norites*, generally very rich in olivine and sometimes nearly of dunitic composition. They occur as very numerous, greater or smaller bosses and bands in the normal olivine-free norite of the marginal zone, but never in the central quartz-norite.

In the marginal zone they occur irregularly distributed all through it from the outer contact with the schists toward the inner border against the quartz-norite and all around it, quite as numerous in the upper as in the lower part of the eruptive. They strike one as being swimming bodies in the norite magma. It is easily proved that they are neither younger intrusions nor older inclusions, but are very nearly of the same age as the environing norite.

While the above-named groups of rocks are all very nearly related and form a stepwise but nearly continuous series without definite eruptive contacts, there is chemically and tectonically a gap between these and a last group of eruptive rocks. The latter form well-defined dikes, cutting all the former rocks and consisting of an aplitic *soda-rich granite*. That they belong to the same eruptive series, with their source in the central part of the lens, is proved by the fact that they are confined to the norite field and occur in greatest quantity in the central field of quartz-norite. Here they form a network of narrow dikes, occupying about 7 per cent of the total area. The dikes are well defined, but with slightly blurred contacts. The same dikes occur also in the marginal norite, here only occupying about 3 per cent of the area, but more regularly and with razor-sharp contacts.

The very last products of volcanic action are some irregular veins of pegmatitic *potash-granite* and of snow-white, pure *quartz*, both carrying black tourmaline.

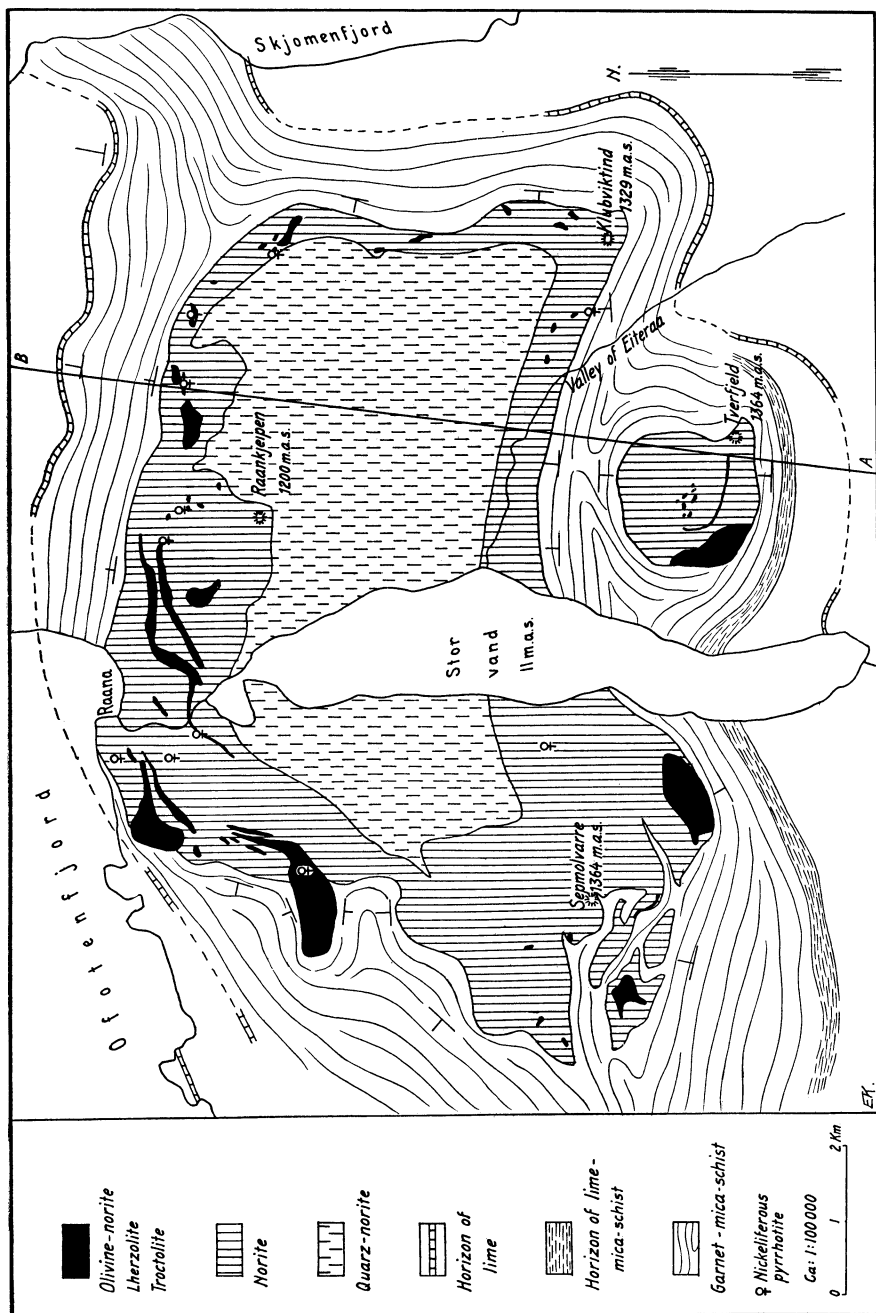


FIG. 1.—Map of the Raana norite field. Scale, 1:100,000

The distinct gap between the main mass of massive norites and the dike-formed acid differentiation products of aplitic granite

reminds us very much of corresponding features of the "red rock" in the Duluth gabbro.¹

The deposits of nickeliferous pyrrhotite—which will not be treated here—are in their occurrence confined to the olivine-bearing rocks and to the marginal normal norite, and no traces of them are found in the quartz-norite or the younger dikes. In the olivine rocks the sulphides occur only as impregnations, but are relatively very rich in nickel. While the percentage of sulphur generally is between 1 and 2 per cent, the nickel content nevertheless reaches 0.7 per cent, of which not more than 0.1 per cent seems to be in the form of silicate in the olivine mineral. In the norite, the sulphides occur partly as impregnations, partly as segregated richer masses, but the nickel content in the pure sulphide is lower, generally between 1.5 and 4 per cent.

The mineralogical composition of the rocks is as follows:

The *olivine-bearing rocks* consist of olivine, rhombic and monoclinic pyroxene, and plagioclase, but generally no primary biotite. Acces-

sory constituents are picotite, green spinel, magnetite, and pyrrhotite. The rhombic pyroxene is an enstatite with less than

¹ Frank F. Grout, "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI, pp. 626 ff.

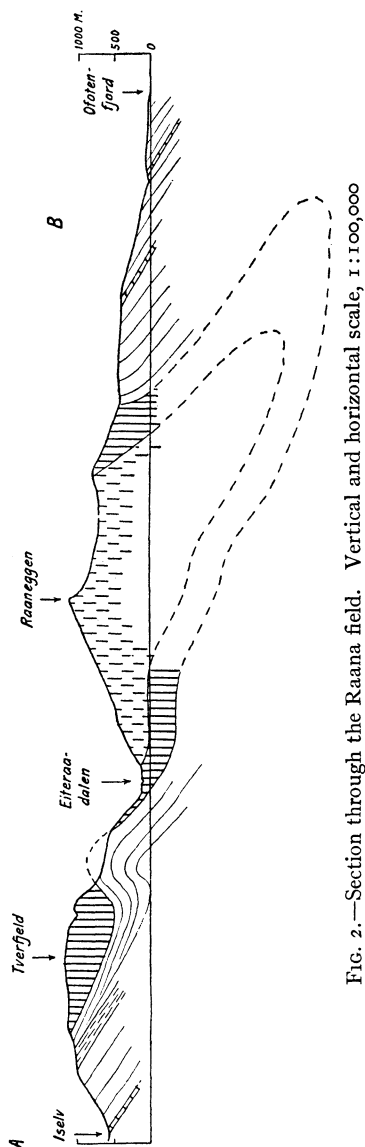


FIG. 2.—Section through the Raana field. Vertical and horizontal scale, 1:100,000

17 per cent ferrous silicate, the monoclinic pyroxene is a diallage. The plagioclase is always bytownite, about $\text{Ab}_{20}\text{An}_{80}$, nearly without zones, and occurring interstitially between the other minerals.

In the *normal norite* the minerals are: Hypersthene with about 25 per cent ferrous silicate, poikilitic diallage in big individualt with hypersthene inclusions, labradorite-bytownite, often with zonal structure and varying composition, from 50 to 80 per cent An, and some primary biotite. Uralitization occurs in many parts of the field, but has no interest in this connection. The considerable variations in this rock seem exclusively to be due to quantitative variations in the relative proportion of pyroxene and plagioclase. The monomineralic rocks, anorthosite or pyroxenite, are however, never developed.

The *quartz-norite* contains iron-rich hypersthene with 40–45 per cent ferrous silicate, much diallage, which is here not poikilitic, but crystallized at the same time as the hypersthene, and further generally plenty of biotite. The plagioclase is labradorite with marked zonal structure, from 40 to 55 per cent An. Besides, this rock always contains small amounts of microcryptoperthitic orthoclase, rich in natron, and of free quartz.

The *aplitic granite* dikes contain quartz, oligoclase with 26 per cent An, non-perthitic microcline, and a little muscovite and biotite.

The *pegmatitic granite* dikes contain quartz, perthitic microcline with a faint green color, and black tourmaline. The perthite consists of 87 per cent microcline and 13 per cent albite-oligoclase with the composition $\text{Ab}_{83}\text{An}_{17}$.

The *chemical composition* of the differentiation products is seen from the analyses in the following table, where the calculated norm is also given.

The mode of these rocks naturally differs somewhat from the norm, even apart from secondary processes. So the potash, instead of forming orthoclase, partly enters into plagioclase and biotite, while part of the lime together with alumina enters pyroxenes instead of plagioclase.

After an exact microscopic measurement, I give the mineral composition actually found in the normal norite and the quartz-norite, corresponding to the analyses No. 3 and No. 6 respectively.

ANALYSES

| | (o) | 1 | 2 | 3 | 4 | (4a) | 5 | 6 | 7 |
|--------------------------------------|--------|--------|--------|--------|-------|-------|--------|--------|--------|
| SiO ₂ | 52.6 | 41.74 | 41.32 | 52.30 | 50.10 | 50.10 | 50.70 | 55.90 | 72.20 |
| TiO ₂ | 0.4 | 0.12 | 0.08 | 0.62 | ..... | 0.5 | 0.25 | 0.45 | 0.39 |
| Al ₂ O ₃ | 16.2 | 2.87 | 7.71 | 10.28 | ..... | 18.5 | 20.70 | 17.50 | 14.22 |
| Fe ₂ O ₃ | 0.5 | 2.96 | 1.83 | 0.37 | 26.75 | 0.5 | 0.50 | 0.08 | 0.55 |
| FeO..... | 6.7 | 10.66 | 8.63 | 8.80 | ..... | 6.3 | 4.38 | 6.97 | 2.00 |
| MnO..... | 0.1 | 0.35 | 0.13 | 0.20 | ..... | 0.10 | 0.07 | 0.09 | 0.03 |
| MgO..... | 12.2 | 38.70 | 35.26 | 18.30 | 12.54 | 12.54 | 9.43 | 5.98 | 1.03 |
| CaO..... | 7.7 | 1.48 | 2.22 | 6.06 | 8.65 | 8.65 | 10.35 | 8.32 | 2.60 |
| BaO..... | Trace | ..... | None | Trace | ..... | ..... | Trace | Trace | 0.02 |
| Na ₂ O..... | 1.8 | 0.63 | 0.54 | 1.14 | ..... | 1.5 | 1.58 | 2.75 | 2.55 |
| K ₂ O..... | 1.0 | 0.24 | 0.98 | 0.58 | ..... | 0.6 | 0.69 | 1.50 | 3.78 |
| P ₂ O ₅ | 0.05 | 0.09 | 0.06 | 0.05 | ..... | 0.05 | Trace | 0.05 | 0.08 |
| V ₂ O ₅ | 0.06? | ..... | ..... | ..... | 0.09 | 0.09 | ..... | ..... | ..... |
| S..... | 0.06+ | 0.12 | 0.28 | 0.09 | ..... | 0.05 | 0.05 | 0.05 | Trace |
| Ni..... | ..... | 0.14 | 0.36 | ..... | ..... | ..... | ..... | ..... | ..... |
| Cr ₂ O ₃ | 0.06 | 0.05 | 0.10 | ..... | 0.09 | 0.09 | 0.08 | None | Trace |
| Cl..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | Trace |
| F..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | Trace |
| CO ₂..... | ..... | None | None | 0.61 | ..... | ..... | 0.40 | 0.20 | 0.06 |
| H ₂ O+..... | 0.7+ | 0.25 | 0.39 | 0.86 | ..... | 0.7 | 1.12 | 0.50 | 0.65 |
| H ₂ O-..... | ..... | (0.03) | (0.04) | 0.06 | ..... | ..... | 0.07 | 0.07 | 0.06 |
| Total..... | 100.13 | 100.40 | 99.89 | 100.32 | ..... | ..... | 100.37 | 100.41 | 100.22 |
| +O for S..... | ..... | 0.06 | 0.14 | 0.05 | ..... | ..... | 0.03 | 0.03 | 0 |
| Total..... | ..... | 100.34 | 99.75 | 100.27 | ..... | ..... | 100.34 | 100.38 | 100.22 |

CALCULATION OF THE NORM

| | (o) | 1 | 2 | 3 | 4 | (4a) | 5 | 6 | 7 |
|------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Quartz..... | ..... | ..... | ..... | ..... | ..... | ..... | 0.66 | 4.48 | 34.74 |
| Orthoclase..... | 6.12 | 1.39 | 6.12 | 3.34 | ..... | 3.34 | 3.80 | 8.88 | 22.24 |
| Albite..... | 15.20 | 5.24 | 3.99 | 9.43 | ..... | 12.58 | 13.62 | 23.23 | 21.48 |
| Anorthite..... | 33.08 | 4.31 | 11.12 | 21.41 | ..... | 41.98 | 47.26 | 30.88 | 12.79 |
| Nefeline..... | ..... | ..... | 0.39 | ..... | ..... | ..... | ..... | ..... | ..... |
| Corundum..... | ..... | ..... | 1.53 | ..... | ..... | ..... | ..... | ..... | 1.22 |
| Σ sal..... | 54.40 | 10.94 | 23.15 | 34.18 | ..... | 57.90 | 65.43 | 67.47 | 92.47 |
| Diopside..... | 2.44 | 1.65 | ..... | 3.56 | ..... | 0.89 | 1.33 | 7.20 | ..... |
| Hypersthene..... | 39.82 | 5.92 | ..... | 56.26 | ..... | 31.95 | 30.20 | 23.45 | 5.84 |
| Olivine..... | 0.62 | 76.52 | 72.72 | 1.08 | ..... | 6.88 | ..... | ..... | ..... |
| Magnetite..... | 0.70 | 4.41 | 2.55 | 0.46 | ..... | 0.70 | 0.70 | 0.12 | 0.70 |
| Ilmenite..... | 0.76 | 0.22 | 0.15 | 1.22 | ..... | 0.91 | 0.46 | 0.85 | 0.76 |
| Apatite..... | ..... | 0.34 | ..... | 0.12 | ..... | ..... | ..... | 0.12 | ..... |
| Chromite..... | ..... | ..... | 0.15 | ..... | ..... | 0.15 | 0.10 | ..... | ..... |
| Pyrite..... | ..... | 0.22 | 0.53 | 0.17 | ..... | 0.10 | 0.10 | 0.10 | ..... |
| Σ fem..... | 44.34 | 89.28 | 76.10 | 63.77 | ..... | 41.58 | 32.92 | 31.83 | 7.30 |
| MgO:FeO ^{mol} | 3.5:1 | 7.3:1 | 7.3:1 | 4:1 | ..... | ..... | 4.3:1 | 1.6:1 | 1:1 |

KEY TO THE TABLE OF ANALYSES

| No. | Petrographic Name | Symbol | Locality | Analyst |
|---------|--|--------------------------|-------------------------|---------------|
| (o) .. | Calculated composition of undifferentiated magma | III 5.4.4 | ..... | ..... |
| 1..... | <i>Lherzolite</i> | (IV) V. 1.1 " 5.1. (1) 2 | Raanbog River | Naima Sahlbom |
| 2..... | <i>Troctolite</i> | IV 1.5.1.1 (2) | Tverfjeldet | Naima Sahlbom |
| 3..... | <i>Normal norite</i> | (III) IV 1.1.1.1. 2 | Source of Raanbog River | Olaf Røer |
| 4..... | <i>Normal norite</i> | Partial analysis | Source of Raanbog River | Naima Sahlbom |
| (4a) .. | Calculated after 4 | " III 5.4.4 | ..... | ..... |
| 5..... | <i>Uralitized norite</i> | II " 5.4.4 | Arnesskaret | Olaf Røer |
| 6..... | <i>Quartz-norite</i> | II " 5.5. (3) 4.4 | Stemnes in Raana | Olaf Røer |
| 7..... | <i>Aplitic granite</i> | I " 3 (4). 2 (3). 3 | Sepmolvarre | Olaf Røer |

While the composition of the quartz-norite is pretty uniform throughout, the marginal norite varies considerably. The analysis No. 3 represents a type very rich in hypersthene, analysis No. 5 a type rich in plagioclase, and analysis No. 4 a mean type.

| | Normal Norite, No. 3 Weight Percentage | Quartz-Norite, No. 6 Weight Percentage |
|---------------------------|---|---|
| Quartz..... | None | 2.1 |
| Orthoclase..... | None | 4.7 |
| Plagioclase..... | 20.0 (ca. Ab ₄₀ An ₆₀) | 59.2 (Ab ₅₃ An ₄₇) |
| Diallage..... | 4.6 | 16.6 |
| Hypersthene..... | 50.2 | 11.0 |
| Biotite..... | 7.3* | 3.8* |
| Amphibole, secondary..... | 16.1 | Very little |
| Magnetite+ilmenite..... | 1.4 | 2.4 |
| Pyrrhotite..... | 0.2 | 0.2 |
| Rutile..... | 0.2 | None |
| Total..... | 100.0 | 100.0 |

* A special case. Generally there is more biotite in the quartz-norite than in the normal norite.

By the aid of the seven analyses stated above we may calculate the mean composition of the four main groups of rocks occurring in the field. They are as follows:

| | Olivine-bearing Rocks | Marginal Zone of Normal Norite | Central Field of Quartz- Norite | Aplitic Granite Dikes |
|--------------------------------------|--------------------------|--------------------------------------|---------------------------------------|--------------------------|
| SiO ₂ | 41.53 | 50.80 | 55.90 | 72.20 |
| TiO ₂ | 0.10 | 0.44 | 0.45 | 0.39 |
| Al ₂ O ₃ | 5.29 | 16.99 | 17.50 | 14.22 |
| Fe ₂ O ₃ | 2.40 | 0.44 | 0.08 | 0.55 |
| FeO..... | 9.64 | 6.47 | 6.97 | 2.00 |
| MnO..... | 0.24 | 0.14 | 0.09 | 0.03 |
| MgO..... | 36.98 | 13.20 | 5.98 | 1.03 |
| CaO..... | 1.85 | 8.43 | 8.32 | 2.60 |
| BaO..... | None | Trace | Trace | 0.02 |
| Na ₂ O..... | 0.59 | 1.43 | 2.75 | 2.55 |
| K ₂ O..... | 0.49 | 0.60 | 1.50 | 3.78 |
| P ₂ O ₅ | 0.07 | 0.03 | 0.05 | 0.08 |
| Vd ₂ O ₃ | | 0.09 | | |
| S..... | 0.20 | 0.06 | 0.05 | Trace |
| Cr ₂ O ₃ | 0.08 | 0.09 | None | |

These variations are illustrated in the diagram of the differentiation processes (Fig. 3).

By measurement from the exact geological maps of the field we find the areal distribution of the main rock groups to be the following:

| | |
|---------------------------------|------------------|
| | km. ² |
| Quartz norite | 30.0 |
| Normal norite | 33.2 |
| Olivine-bearing rocks | 3.8 |
| Total | 67.0 |

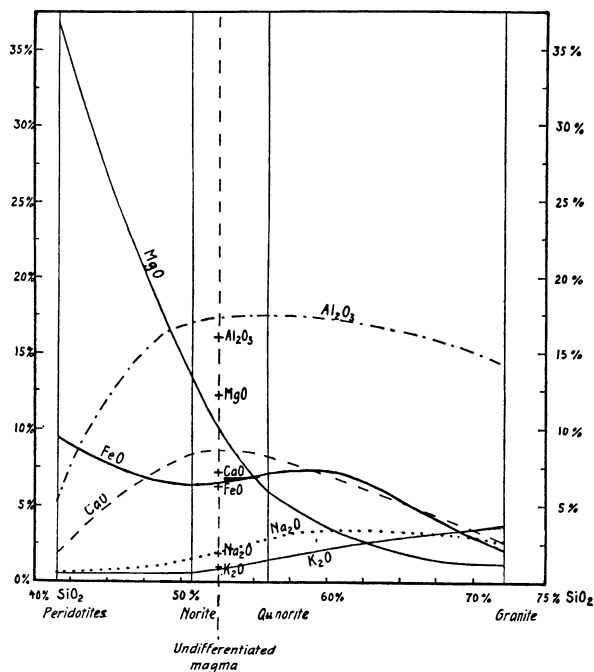


FIG. 3.—Differentiation diagram, based upon the mean composition of the main rock groups.

After the modifications necessary for the topographical irregularities, after recalculation to weight percentage, and after introducing the calculated quantity of the granite dikes, the proportion becomes the following:

| | |
|---------------------------------|-------------------|
| | Weight Percentage |
| Aplitic granite | 3.9 |
| Quartz norite | 31.3 |
| Normal norite | 57.4 |
| Olivine-bearing rocks | 7.4 |
| Total | 100.0 |

It may be noted here that these percentages are not proportional to the areal distribution of the rocks at the surface, because the quartz-norite and the normal norite without doubt are concentrically arranged throughout the field, so that any section through the center of the field will give the same image. Accordingly, their relative volume is with the greatest approximation calculated here after the formula for concentric spheres.

After the results given above, stating the quantitative proportion and the chemical composition of the main groups of rocks, we are in the rare and happy position to be able to state—with a fair amount of accuracy—the mean composition of the whole field, representing the original, undifferentiated eruptive magma. This composition is given in column o, in the table of analyses. The most remarkable feature is the very high magnesia content in connection with the relatively high silica content. It is an ideal norite magma.

The regular, stepwise development of the differentiation products is best seen from the norm calculations. Not only the chemical composition changes along definite lines, but also the composition of the individual minerals, especially the plagioclase and the rhombic pyroxene. Very remarkable is the regular change in the ratio $\text{MgO}^{\text{mol}}:\text{FeO}^{\text{mol}}$ in the silicates, decreasing markedly toward the salic rocks. The reason for this appears from what follows.

THE DIFFERENTIATION PROCESS

Starting with a study of the known forsterite-diopside-silica and the forsterite-anorthite-silica diagrams,¹ we learn that in the mean, undifferentiated magma of the Raana field, nearly without olivine in the norm, olivine will anyway be the first mineral to crystallize—beginning at the border toward the surrounding schists—and it will continue to separate out until the eutectical line olivine-pyroxene is reached. By further cooling, rhombic pyroxene crystallizes out at the same time as the *already formed olivine crystals are resorbed*.

If this process continued undisturbed, the final result would be an olivine-free rock, corresponding to the norm. However, we find

¹ See N. L. Bowen, *Jour. Geol.*, Vol. XXIII, suppl., pp. 20 and 29.

in the field, as stated above, a series of olivine-rich rocks all around the marginal zone of the eruptive body and of nearly the same age as the environing norite. These olivine rocks can only have been individualized during that period of the crystallization process when free olivine crystals were really suspended in the crystallizing marginal zone. It is obvious that even the slightest accumulation of these crystals at certain places would at once bring them in excess, and prevent them from being wholly resorbed.

Consequently, olivine would become a part of the norm composition at those places. We may conclude, therefore, that such an accumulation of olivine crystals has really taken place. That gravity separation has not played a prominent part in it is obvious from the distribution of the olivine rocks. We are forced to conclude that convection currents and other movements in the magma have been able to bring about such an accumulation, possibly also a conglutination of already formed crystals.

The explanation is confirmed by two facts: First, in all the olivine rocks the olivine crystals are surrounded by resorption rims, proving that resorption has been going on, but stopped at a certain point. Secondly, the olivine crystals in all these fields have nearly the same proportion, $\text{Mg}_2\text{SiO}_4:\text{Fe}_2\text{SiO}_4$, quite independent of the quantity of olivine, and consequently have all separated out from a uniform magma.

We get a natural explanation of the varying quantities of plagioclase and pyroxenes in the olivine rocks and of their "swimming" character in the norite magma.

After the termination of the resorption period and the consolidation of the olivine rocks, the rest of the magma in the marginal zone should obviously be expected to have become poorer in magnesia and richer in silica than the magma of original composition in the still fluid central part. Field observations teach us, however, that the olivine-free norite in a very thick marginal zone has a more basic composition than the central part.

To explain this, we might think of compensating currents in the magma prior to the resorption period, which in combination with the resorption of some of the olivine might produce this basic

composition. Chemical calculations, however, show this to be impossible, and the differences in the composition of the plagioclase point in the same direction.

We might also consider another sort of differentiation, according to which the marginal zone of the massive represents the mean, original composition of the magma, intruded by younger femic and salic differentiation products. The evident field observations, however, contradict such a supposition also.

Here, therefore, the squeezing theory, as developed by N. L. Bowen (*loc. cit.*), turns out to be a very natural and obvious explanation.

It must be remembered that the process takes place under orogenic pressure. While the segregated crystals are only suspended in the magma, the pressure is static and has no influence on the differentiation. From the moment when the outmost shell forms a fixed crystal mesh, this shell has eventually to take up the mountain pressure, but, of course, at first is not able to do so. The pressure then will be dynamic. Following Bowen, this stage is supposed to occur when about 80 per cent of the mass is crystalline and only 20 per cent liquid.

As the volume of the magma is diminished by cooling and still more by crystallization, the outer shell will be compressed and its remaining interstitial liquid squeezed out. At that advanced stage of crystallization, this liquid will contain plagioclase, richer in soda, and pyroxene, richer in iron and lime than the already segregated crystals, moreover eventually potash-feldspar, free quartz, and magmatic water.

These components accordingly will move, and the direction of movement will be inward from the zone of dynamic into the zone of static pressure, because in the crystallizing zone with still static pressure the diminishment of volume will have the effect of releasing the pressure.

It is important to note that the process is here not supposed to be a squeezing for a long distance through a crystal mesh. Probably it is mainly a differential movement, restricted to the narrow transition zone, which moves inward at the same rate as the crystallization proceeds.

“The wave of crystallization is followed by a wave of squeezing.” Continually the squeezed material will mix with the more fluid magma inside, which gradually becomes more acid.

The next step is the abrupt transition from the normal norite of the marginal zone to the quartz-norite of the central part. This is very easy to explain. It represents the stage when the outer, solid shell has grown sufficiently thick and strong to resist the compressing forces. From that moment no more compression and no more squeezing takes place. The remaining magma crystallizes quietly without further differentiation to a uniform quartz-norite, carrying a little free quartz and orthoclase, more acid plagioclase, and much biotite on account of enrichment of the magmatic water.

Of course, the contraction or the release of pressure continues as the crystallization proceeds, and finally results in a general formation of fissures in all directions, when the resulting stresses have grown sufficiently strong.

This fissuring obviously occurred at a stage when the quartz-norite was consolidated, with exception of the very last interstitial liquid, containing a considerable proportion of magmatic water and mineralizers. The liquid was drained into the fissures, forming aplitic dikes of soda-rich granite. This last separation is obviously not due to squeezing; but whether the liquid was really sucked out into the fissures or driven out by the pressure of the enriched gaseous mineralizers is difficult to tell. At any rate, there resulted a direct connection between these dikes and the last consolidated minerals in the quartz-norite, producing the slightly blurred contacts mentioned above.

Also in the marginal normal norite, clefts were formed at this period and filled with the same dikes of granite. Here they have razor-sharp contacts because the marginal rock at that time was completely solid.

The mineralizers once more separated out, carrying with them much potash and silica and giving rise to veins of pegmatite and pure quartz, both rich in tourmaline.

From the foregoing we see that the theory as modified covers all the observed facts. It is beyond doubt that the differen-

tation proceeded quite *in situ* and is confined to the crystallization period. Further we have learned that the squeezing differentiation gives results which in many respects are similar to those of gravitative separation. In the one case the liquid is removed from the crystals, in the other case the crystals from the liquid.

There is only one point left which cannot yet be explained in detail: how some of the primary olivine crystals could be brought to accumulate or conglutinate at certain places. On this point, therefore, we can only state the fact and remark that any supposition of immiscibility of olivine with the rest of the magma, resulting in the formation of fluid drops of olivine, would not help us, but be in opposition to several of the above-stated facts.

As will easily be seen, the special differentiation type of Raana is not apt to occur very frequently. It presupposes the following conditions: (1) the crystallization must take place under lateral pressure; (2) it must take place completely *in situ*, in a closed room without supply of new magma during the process; (3) gravitative separation must not play a prominent part.

In the same district we meet a somewhat different type of squeezing differentiation, one which will prove to have a more general occurrence in orogenic folding zones. It occurs when the central part of the eruptive mass is not—as in Raana—protected against lateral pressure. A short statement of it is here added.

THE AMPHIBOLITE SERIES

As mentioned in the first part of this paper, in the folded mountain region there occur considerable quantities of femic eruptive rocks very intimately injected into the schists and completely recrystallized through dynamic metamorphism. They do not occur in so extensive individual masses as do the fresher rocks of the Raana type, but they are much more widely distributed. Chemically they have diabasic composition and differ from the corresponding rocks of the Raana field in carrying more iron in proportion to magnesia, more sodium, titanium, and phosphorus.

On account of the total parallelism of all eruptive injections in the district, direct observations of relative ages can generally not

be made. The amphibolites *might* be somewhat older than the Raana norites and accordingly have been subject to a longer period of dynamic metamorphism during the Caledonian folding. But the reason for the different degree of metamorphism might also be that the process has been able to act more severely upon these rocks on account of their lesser thickness and their very intimate injection in the surrounding schists—which show about the same degree of metamorphism—while the massives of the Raana type have resisted better.

The mineral composition of the ordinary amphibolites is: amphibole and acid plagioclase as the predominant minerals, more or less epidote or clinozoisite, quartz, leucoxene, and often garnet and biotite. None of the primary minerals are left.

The original basic plagioclase has been more or less albitized, producing plagioclases from albite to oligoclase composition, while part of the lime enters the epidote minerals. The original pyroxenes have been changed to amphibole, and it is noteworthy that while in the Raana field the uralitization has produced a nearly colorless amphibole of actinolitic composition, poor in alumina, the metamorphic rocks contain common green amphibole, rich in alumina.

The differentiation shows several features analogous to those just described from the Raana field, but also significant differences.

In many of the amphibolite zones we find a number of small bosses of serpentine rocks, very irregularly distributed. The dozens of such bosses observed nearly always occur within the amphibolite rock and are not separately injected into the schists. They are all of relatively small dimensions, rounded or lens-shaped, and sharply defined from the surrounding amphibolite. They obviously correspond to the peridotitic rocks of the Raana field, but are always completely metamorphosed to serpentine and talc minerals.

In numerous cases the amphibolite itself is nearly homogeneous, and without intermediate steps there is a wide gap over to soda-rich granites which occur nearly everywhere in intimate connection with the amphibolite series in such a way that there can be no doubt of their mutual relation as differentiation products.

Here the granite does not occur as crossing dikes, but as small lenses or bands arranged parallel to the schistosity of the amphibolites. In some cases they occur as separate sheets of considerable thickness in or at the border of the amphibolite. Only in rare cases, when the amphibolite has retained a more massive structure without marked schistosity, do they occur as numerous crossing, irregular stringers cutting the femic rock.

The contrast between the two rocks is still more marked than was the case in the Raana field on account of the great difference in chemical composition and the different degree of metamorphism. While the amphibolites are completely recrystallized, the granitic differentiates have retained much of their original structure, partly because they are somewhat younger, partly because the granitic mineral association has by far not the same tendency toward mineral readjustment under new conditions as is the case with the femic rocks.

These granites are characterized as soda-rich, but their composition may differ somewhat. Sodium may be quite predominant among the alkalis, the rock becoming a *Trondhjemite* as described by V. M. Goldschmidt from the Trondhjem district farther south. By increasing potash they get a more granodioritic composition, up to a limit with about equal molecular amounts of soda and potash. In all cases they are poor in dark minerals and generally have aplitic structure.

They are distinctly different from the ordinary granites in the district, which occur as great independent eruptions, and where the potash is always predominant.

The chemical composition of the ordinary amphibolite and its granitic differentiate is seen from the analyses on page 719.

In some cases we meet intermediate rocks between the amphibolitic and granitic extremities, mainly of dioritic composition. The variations are never regular, but form "schlieric" or banded alternations in the schistose rock.

From the foregoing we have seen that the characteristic regular differentiation step between the normal norite and the quartz-norite in the Raana field has no correspondent in the amphibolite series. This is a natural consequence of the fact that here the

central part of the mass was not protected against the lateral pressure which prevailed during the whole crystallization.

The result of the differential squeezing during the crystallization period has therefore been the ultimate separation of the last consolidating constituents of the magma. During the continued pressure after crystallization of the main rock mass, this last residue has been squeezed into the already consolidated rock as

| ANALYSES | | | CALCULATION OF THE NORM | | |
|--------------------------------------|--------|--------|--|--------|-------|
| | No. 8 | No. 9 | | No. 8 | No. 9 |
| SiO ₂ | 49.12 | 67.49 | Quartz..... | 3.36 | 19.74 |
| TiO ₂ | 2.46 | 0.29 | Orthoclase..... | 2.22 | 11.12 |
| Al ₂ O ₃ | 13.70 | 16.52 | Albite..... | 22.01 | 48.73 |
| Fe ₂ O ₃ | 1.95 | 2.33 | Anorthite..... | 24.46 | 13.34 |
| FeO..... | 10.67 | 0.34 | Corundum..... | | 0.10 |
| MnO..... | 0.18 | 0.03 | Σ sal..... | 52.05 | 93.03 |
| MgO..... | 5.19 | 0.88 | Diopside..... | 17.51 | |
| CaO..... | 11.02 | 3.43 | Hypersthene..... | 18.17 | 2.20 |
| BaO..... | Trace | Trace | Hematite..... | | 2.24 |
| Na ₂ O..... | 2.58 | 5.76 | Magnetite..... | 2.78 | |
| K ₂ O..... | 0.44 | 1.93 | Ilmenite..... | 4.71 | 0.61 |
| P ₂ O ₅ | 0.22 | 0.50 | Apatite..... | 0.52 | 1.34 |
| S..... | 0.10 | 0.10 | Pyrite..... | 0.36 | 0.19 |
| CO ₂ | 1.21 | None | Σ fem..... | 44.05 | 6.58 |
| H ₂ O+..... | 1.37 | 0.81 | MgO ^{mol} :FeO ^{mol} | 1.24:1 | |
| H ₂ O÷..... | 0.01 | (0.05) | | | |
| Total..... | 100.31 | 100.41 | | | |
| ÷O for S..... | 0.10 | 0.05 | | | |
| Total..... | 100.21 | 100.36 | | | |

KEY TO THE TABLE OF ANALYSES

| No. | Petrographic Name | Symbol | Locality | Analyst |
|-------|---------------------------|--------------------|-----------------|---------------|
| 8.... | <i>Garnet-amphibolite</i> | III. " 5. " 4. " 5 | Björkaasen Mine | Olaf Røer |
| 9.... | <i>Aplitic granite</i> | I " .4. 2. 4 " 5 | Brugsaa | Naima Sahlbom |

lenses, stringers, and bands of aplitic granite. Their ordinary arrangement parallel to the schistosity shows that this must have been partly developed already during the consolidation as crystallization schistosity.

The magmatic water and mineralizers with their dissolved substances seem to have taken their own path, having a more active power of motion contrary to the purely passive motion of the ordinary squeezed material.

They have given rise to replacement phenomena and formation of ore deposits, still younger than the aplitic granite.